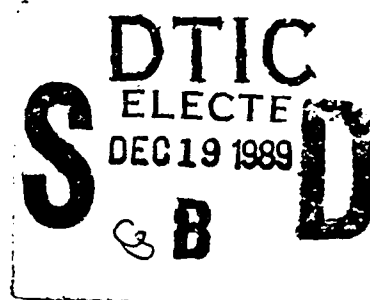


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DEVELOPMENT OF A PARALLEL LINK MODEL  
FOR METEOR BURST COMMUNICATION

THESIS

Ryan Curtis Cochran  
Captain, USAF

AFIT/GE/ENG/89D-7

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

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Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Electrical Engineering

Ryan Curtis Cochran, B.S.E.E  
Captain, USAF

December, 1989

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## *Preface*

The purpose of this thesis effort is to present a model of a parallel meteor burst communication (MBC) link. The interest in this topic stems from the need to improve the throughput and waiting time performance of MBC systems. Emphasis was placed on simulation, queueing effects and the engineering factors effecting the meteor burst communication process. A review of meteor burst communication theory is given along with a discussion of the basic MBC propagation fundamentals. however, for a more detailed explanation, the references found in the bibliography should be reviewed.

The results obtained in this study were determined over a twelve month period. I am deeply grateful to my thesis advisor, Lt Colonel Dave Norman, for his guidance and support throughout this effort. I would also like to thank my committee members, Major Glenr Prescott, Major Harry Barksdale and Captain Bill Hodges.

Finally, I wish to thank my wife Dorothy for her patience and support throughout this graduate program.

Ryan Curtis Cochran

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### *Abstract*

Meteor burst communication (MBC) constitutes an unusual propagation medium with many unique and interesting properties. These properties make MBC well suited for military applications. MBC offers many advantages over other forms of existing long range communication systems. Some of the advantages include low probability of intercept (LPI), antijam (AJ), flexibility and survivability. The LPI/AJ characteristics of MBC are the most important to military applications. MBC also suffers from two major drawbacks: long message delay times and low throughput. As a result, MBC systems exhibit low average data rates and long delay times. In order for MBC to gain widespread use, methods to optimizing system performance must be developed. The result of this study effort is the development of a parallel MBC link model that is used to analyze MBC network performance.

To address this issue, a computer model was developed to emulate a PAVE PAWS parallel link MBC network. This unique model was developed using the queueing model for a MBC channel. The queue used is a M/G/1 queue with server vacations. The model was implemented using two simulation programs which are supported on the IBM PC. The results of the simulation are validated by comparison to analytical data.

The results gathered in this study effort indicate that some performance gains are attainable if a MBC network is modeled using a parallel link model. It is shown that moderate increases in throughput and a reduction in message waiting time is possible.

# DEVELOPMENT OF A PARALLEL LINK MODEL FOR METEOR BURST COMMUNICATIONS

## *I. Introduction*

Meteor burst communication (MBC) systems use meteor trails to reflect signals for information transfer. The effects of meteor burst were discovered in the early 1950s by ham radio operators. Since then many studies have been conducted to investigate the full potential of this unique form of communication media. This thesis will be dedicated to the development of a parallel link model of a meteor burst communications channel.

### *MBC Basics*

As the Earth moves through its orbit each day, it sweeps up billions of meteors. As these meteors enter the earth's atmosphere, they burn, causing short duration ionization trails. Meteors with a mass greater than a microgram create trails capable of reflecting radio signals. The rate meteors arrive at any location varies from hour to hour, day to day, month to month, and from season to season. These variations are due to the tilt and rotation of the Earth. The frequency of meteor arrivals is more intense in the morning because meteors are swept up by the forward motion of the earth in its orbit around the sun. In the evening the only meteors entering the atmosphere are those with a velocity faster than that of the earth. Seasonal variations occur due to the tilt of the earth, and are more noticeable at the poles than at the equator (28:119-120).

A basic MBC system consists of a master station and one or more remote stations. System operation begins with a master station continuously sending a

coded signal, typically in the 40 to 50 MHz region. When a meteor creates a trail in the proper location, the coded signal is reflected to a remote station. Once the remote station receives the signal, it in turn sends an acknowledgement to the master station. Information flow can take place in either direction as long as the trail can sustain reflections. This initial setup procedure and transfer of information can occur over a time span of milliseconds to seconds (22:55-61). Before the advent of integrated circuit technology, most meteor trail communications consisted of short two-way message transmissions. The computer chip has made it possible to build equipment that can transmit thousands of bits per second during a single trail (16:23-24). The maximum range of a single-hop link (that is, point-to-point) is 2000 km. The height of the trail and the curvature of the earth determine the communication range. Because the arrival of a suitable trail is a random event, communication takes place in the form of high-data rate "bursts" followed by long periods of silence (22:56).

MBC is well suited for military application because of its unique qualities. MBC offers many advantages over existing long range communication systems. Some of the advantages are low probability of intercept (LPI), antijam (AJ), flexibility, and survivability. The LPI/AJ characteristics make MBC a primary choice for a backup wartime communication network. MBC can support a wide variety of requirements, from a simple remote sensor to a complex network. The most significant advantage of MBC over other types of communications is the ability to recover from the electromagnetic effects of atmospheric nuclear explosions in a relatively short time. MBC is simple to implement, inexpensive, and highly reliable (5:86). These advantages make MBC well suited as a back-up communication system for many  $C^3I$  networks.

MBC also suffers from two major drawbacks: long message delay times and low throughput. Most messages require several trails for transmission, due to the short duration of meteor trails. Because of this, MBC networks exhibit low average data rates and long delay times (5:86). The use of MBC systems will increase as

methods are developed to optimize their performance.

The performance characteristics of MBC can be effectively evaluated using analytical and simulation models. With these tools, the effects of network topology, message transmission protocol, routing schemes, and variations in operating parameters can be easily studied. Analytical and simulation models can be used to determine methods to improve network throughput and message waiting time. These advances will make MBC systems more attractive to potential users.

#### *Summary of Past Effort*

Three AFIT theses have explored the area of MBC systems. Captain Donald D. Conklin presented a thesis entitled "Simulation Model of a Meteor Burst Communication System for Data Transmission Protocol Evaluation" in December 1986. The purpose of his thesis was to develop a method of simulating a MBC system so that current data transmission protocols could be modified and tested in an attempt to improve MBC system performance. The simulation model was developed to emulate the RADC high latitude MBC test network. His effort focused on observing the effects of changing various network protocol parameters. Some of the protocol modifications included message length and structure modifications, overhead bit reduction, and adaptive message techniques designed to improve the use of meteor trails. These protocol modifications proved to be successful in improving the data throughput of the RADC network.

Captain Bruce A. Meyers published a thesis entitled "Simulation and Analysis of Networking Techniques in a Multiple Link Meteor Burst Communications Network" in December 1987. The purpose of his effort was to develop a computer simulation model of MITRE's proposed MBC network. His main objective was to determine the effects of static, flood, and adaptive routing algorithms on the network performance. He also performed a simulation of a priority traffic queueing system to determine how it would effect the efficiency of the network.

Captain Brian C. Healy wrote a thesis entitled "A Modeling Perspective for Meteor Burst Communication" in December 1988. The main purpose of his thesis was to develop a generic simulation model for MBC networks. His emphasis was on queueing effects and simulation. He developed a simulation model that could be used for both single and multiple link MBC networks.

The theses that have been accomplished to date only investigated operating MBC networks composed of single links between nodes. Although the information presented in these theses is very useful, a study is needed of the performance of several parallel links between network nodes of a MBC network. The possible advantages include: waiting time reduction, lower probability of error and higher reliability.

#### *Problem Statement*

The problem to be addressed in this thesis is the design of a parallel link model for meteor burst communications channels. The methods used in the development of this model will provide useful information to network designers.

#### *Approach*

To solve this problem, the thesis effort will proceed as follows:

1. Closed form expressions for message throughput and waiting time on a parallel link will be developed from existing formulas for a single link. The derivation of the formula will be based on probability theory. The formula will be extended to include multiple parallel link networks.
2. A message transmission protocol will be selected from existing methods. Performance characteristics such as throughput and waiting time, will be determined using the previously derived expression for parallel links. A computer program will perform this analysis.

3. A survivable network topology will be developed using network design and graph theory. A topology independent of the actual geographical location of proposed sites will be derived. This model will be expanded to accommodate the actual layout of the Integrated Tactical Warning and Assessment (ITW&A) network.
4. The performance characteristics of the parallel link network will be compared to those of a single link model of the same network. The SLAM II simulation language will be used to perform this comparison.

### *Scope*

This effort will be limited to the development and evaluation of a survivable network topology and expressions for waiting time and throughput for the PAVE PAWS segment of the ITW&A communications network sites. No attempt will be made to perform a trade-off analysis between the advantages of increasing transmitter power for a particular link or adding more parallel links.

### *Assumptions*

The following assumptions will be made in this thesis project.

1. An optimal network topology usually cannot be determined. A suitable topology can be approximated given desired values for throughput and delay.
2. Throughput and delay cannot be optimized simultaneously. Throughput and delay are inversely related.
3. Closed form expressions for message throughput and delay only exist for simple message transmission protocols.

These assumptions are not limitations. Assumptions were made to keep the models and analysis as simple as possible.

### *Standards*

The accuracy of the analytical expressions used in the network analysis will be validated by comparing results to data calculated by a simulation model. The simulation model will be verified by computing values for simple test cases and comparing results to empirical data. After the verification process is complete, the validity of any data generated by these methods is established.

### *Overview of Remaining Chapters*

Chapter II provides an overview of the meteor communication phenomenon. Chapter III explains the theory of meteor burst communications. This chapter also provides a discussion of MBC networks, commonly used communication protocols and military applications of MBC. Chapter IV discusses the meteor burst transmission theory. This chapter also describes some of the existing MBC performance measures. Chapter V contains the development of the MBC network model. Chapter VI is a discussion of the results. A comparison to the results obtained from other network models is also made in this chapter. Chapter VII provides recommendations for future research. Appendix A is a glossary of terms. Appendix B contains the detailed equations used to develop the MBC network model.

## *II. Meteor Burst Communication Principles*

Meteor burst communication (MBC) systems use meteor trails to reflect signals for information transfer. Meteor burst effects were discovered in the early 1950s by ham radio operators. Since then many studies have been conducted to investigate the full potential of this unique form of communication media.

### *Basic Concepts*

George Sugar laid the foundation of MBC in his article, "Radio Propagation by Meteor Trails" published in 1964 (28). His article provides an excellent overview of meteor burst theory. As the Earth moves through its orbit each day, it sweeps up billions of meteors. Only those meteors that are completely burned by frictional heating are useful in MBC. Micrometeorites are so small that they are not destroyed as they pass through the atmosphere. Large meteors are not useful in MBC because they occur infrequently. As these meteors enter the earth's atmosphere, they burn, causing short duration ionization trails. Useful trails are formed by meteors having a mass ranging from  $10^3$  to  $10^{-7}$  grams and dimensions in the range of 8 centimeters to 40 microns.

Meteors are divided into two classes: shower meteors and sporadic meteors. Shower meteors are large clouds of particles moving at the same velocity, entering the atmosphere of the earth at a specific time each year. The infrequent occurrence of meteor showers account for only a small percentage of all meteors. It is the nonshower or sporadic meteors which provide nearly all the trails used in radio propagation. Unlike shower meteors, sporadic meteors do not have well defined orbits or exact times of occurrence (28:119-121). The orbits of sporadic meteors are uniformly distributed, concentrated in the earth's orbital plane and move in the same direction as the earth. This distribution tends to produce a maximum incidence of meteors in July and a minimum in February for the northern hemisphere. In the southern

hemisphere, the figures are opposite. The variation between July and February is a 3:1 ratio. The rate of incidence of sporadic meteors is effected by two factors. The first factor is due to the motion of the earth around the sun. This results in diurnal variations in the meteor arrival rate and the average meteor velocity. Arrivals are *greater in the morning because meteors are swept up by the forward motion of the earth in its orbit around the sun.* In the evening the only meteors entering the atmosphere are those with a velocity greater than that of the earth. Figure 2.1 illustrates this point. The arrival rate of meteors reaches its peak around 6 a.m. and is at its lowest around 6 p.m. The daily variation is approximately 4:1.

The difference between the maximum and the minimum arrival rates is also affected by the latitude of the observation point. Variations in the average velocity of meteors causes variations in the trail height; and this in turn causes changes in trail duration. Seasonal variations occur due to the tilt of the earth and are greater at the poles than at the equator (28:119-120). Figure 2.2 shows how the arrival rate varies from month to month.

Sugar's research shows that most useful trails occur in an altitude range of 80 to 120 km (50 to 75 miles) from the Earth's surface (28:121). As meteors collide with the atmosphere, friction causes them to heat and vaporize. The vaporized atoms leaving the meteor's surface collide with those in the atmosphere, ionizing them and leaving a trail of electrons. The electron line density in the trail is proportional to the mass of the particle. The length and duration of meteor trails depend on several factors. The length of the trails is a function of the mass and the angle at which the meteor enters the atmosphere. The typical length of a meteor trail ranges from 15 to 50 km with a radius of 0.55 to 4.35 m. There exists "hot spot" volumes where meteor trails are most likely to occur between two distant ground stations (2:748). Therefore, it is important to point the transmitting and receiving antennas toward these regions to attain maximum performance. The duration of a trail is a function of the mass of the meteor, atmospheric wind and the means of detecting it.

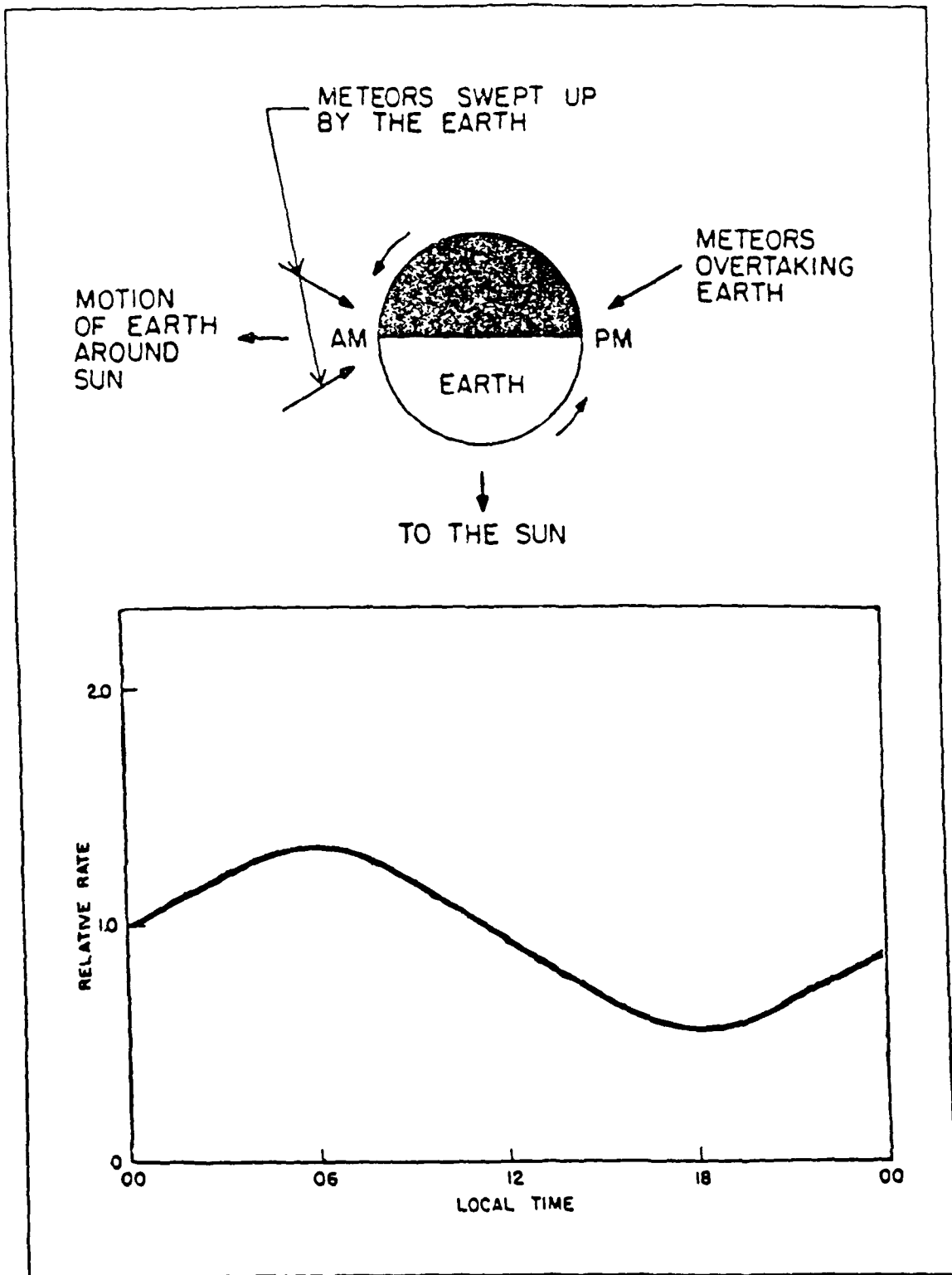


Figure 2.1. Cause of Diurnal Variations (28:121)

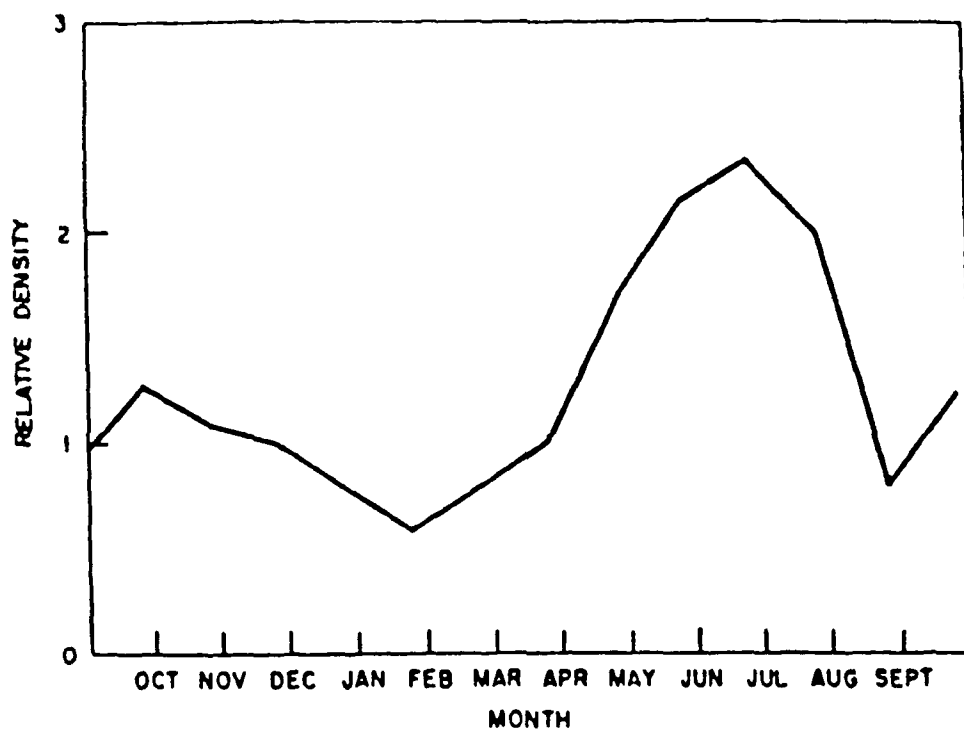


Figure 2.2. Monthly Variations in Meteor Arrivals (28:121)

The trails used in MBC can be divided into two classes: underdense trails and overdense trails. Underdense trails only last a short time while overdense trails last longer. The electron density of underdense trails is low (less than  $2 \times 10^{14}$  electrons/meter). Underdense trails allow penetration by the radio waves, causing the trail to act like individual antennas reradiating the wave in a scattering fashion. Overdense trails have a high electron density and do not allow penetration of radio waves and cause them to reflect. Overdense trails are caused by larger meteors and therefore, occur less frequently. Most trails are formed by micrometeors and last for a few tenths of a second (28:118). Table 2.1 shows the relationship between the mass of meteors and the frequency of occurrence.

Table 2.1. Meteor Size Distribution

(24:9)

Mass (grams)	Radius (cm)	Number Swept up by the Earth per Day	Electron Line Density (electrons/meter)
OVERDENSE TRAILS			
$10^3$	4.0	$10^2$	$10^{20}$
$10^2$	2.0	$10^3$	$10^{19}$
10	0.8	$10^4$	$10^{18}$
1	0.4	$10^5$	$10^{17}$
$10^{-1}$	0.2	$10^6$	$10^{16}$
$10^{-2}$	0.08	$10^7$	$10^{15}$
UNDERDENSE TRAILS			
$10^{-3}$	0.04	$10^8$	$10^{14}$
$10^{-4}$	0.02	$10^9$	$10^{13}$
$10^{-5}$	0.008	$10^{10}$	$10^{12}$

The propagation of meteor trail transmissions can be effected by ionospheric variations. Changes in the ionosphere tend to reflect other VHF signals causing interference for meteor trail signals. Some of these variations are: polar cap absorption, Sporadic E, auroral disturbances and D region disturbances (4:10).

Polar cap absorption (PCA) takes place during periods of high solar flare activity. This phenomenon severely attenuates MBC signals because trail durations are shortened. Only high latitude communications are effected by PCA.

Sporadic E is an ionospheric variation that occurs in the E region of the ionosphere. It is primarily a daytime phenomenon and is nonexistent after sunset. The E layer of the ionosphere extends from 90 to 140 km above the Earth and thus overlaps most of the region where useful meteor trails occur. The Sporadic E condition causes increased ionization in the E region, causing enhanced MBC performance.

Auroral disturbances create a condition called "radio aurora" which is defined as enhanced ionospheric ionization that can reflect radio waves at an altitude ranging from 75 to 135 km. This disturbance causes increased intersymbol interference (ISI) due to multipath spreading. In order for MBC to take place, data rates must be drastically reduced.

The D region is the lowest and densest layer of the ionosphere. It extends from 60 to 90 km above the Earth. Turbulence, wind shears, and other conditions cause fluctuations in the electron density distribution of meteor trails. D region disturbances are very sensitive to operating frequency. Signals with a frequency of 60 MHz or greater are not effected by this condition.

### *III. Meteor Burst Communication Systems*

The concept of meteor burst communications dates back 30 to 40 years. Its real emergence coincided with the advent of satellite communications (23:73). For years, MBC was somewhat ignored because of the popularity of satellite communication systems. A growing concern with the physical and electrical vulnerabilities of satellites brought about renewed interest in MBC systems. Progress in microelectronics has increased the performance capability of current MBC systems over previous systems.

A basic MBC system consists of a master station and one or more remote stations. The system operates with the master station continuously sending a coded signal, typically in the 40 to 50 MHz region. When a meteor creates a trail in the proper location, the signal is reflected to a remote station. Once the remote station receives the signal, it in turn sends an acknowledgement to the master station. Information flow can take place in either direction for as long as the trail can sustain reflections. The initial setup procedure and transfer of information takes place very fast (22:55). Depending on the size of the meteor creating the trail, the path may be useful for a time ranging from a few milliseconds to several seconds. Before the advent of integrated circuit technology, most meteor trail communications were limited to short two-way message transmissions. The computer chip has made it possible to build equipment that can transmit thousands of bits per second during a single trail (16:23-24). The minimum range of a meteor burst system is approximately 400 km. This range is limited because of the angles of incidence and reflection needed to establish a communication path. The maximum range of a single-hop link (i.e. point-to-point) is 2000 km. This distance is determined by the height of the trail and the curvature of the earth. Wait times between usable trails can range from seconds to minutes depending upon daily and annual cycles and on the MBC system design.

Since the arrival of a suitable trail is a random event, communication takes place in the form of high-data rate "bursts" followed by long periods of silence (23:69).

### *Historical Perspective*

Operational MBC networks have been in existence since the early 1950s. Kenneth Kokjer and Thomas Roberts discuss a brief history of MBC in their article "Networked Meteor- Burst Data Communications". One of the first fully operational MBC networks was the Canadian JANET system in the 1950s. It was used for teletype communications between Toronto and Port Arthur, a distance of 1000 km. The JANET system used many of the features found in the systems of today: stored digital data which is transmitted/received in bursts and duplex operation at frequencies around 50 MHz. In the 1960s and 1970s, actual systems were put into use, applying lessons learned from previous studies. One of the notable systems of this time was the COMET (Communication by Meteor Trails) system which was operated between the Netherlands and Southern France. COMET made use of frequency diversity and automatic repeat request (ARQ) which allowed signal repetition if the communication path was lost. The COMET system used a signaling rate of 2000 baud and frequency shift keying (FSK) as its modulation scheme. COMET demonstrated the practicality of meteor burst communications under varied conditions. Also in the 1970s, the U.S. Department of Agriculture established a netted system called SNOTEL (Snow Telemetry), which is still in use today. SNOTEL consists of several hundred sites located in the western part of the country. These remote sites are used to collect data on snow accumulation and rain fall (16:24).

### *Military Applications*

For many years, MBC technology has been studied to determine its military value. MBC is well suited for military application because of its unique qualities. MBC offers many advantages over existing long range communication systems. Some

of the advantages are low probability of intercept (LPI), anti-jam (AJ), flexibility, and survivability. The LPI/AJ characteristics apply only to beyond line of sight (BLOS) communications. Based on the small footprints of meteor trail communications, BLOS interception by unintended receivers is statistically unlikely, as is BLOS jamming from trail to trail. Flexibility means that MBC can support a wide variety of requirements, from a simple remote sensor to a complex network. The most significant advantage MBC has over other types of communications is the ability to recover from the electromagnetic effects of atmospheric nuclear explosions in a short time. Hardware advantages of meteor burst over HF include smaller antennas and less complex equipment. The two primary disadvantages of MBC are long message delay times and minimum transmission range. Because of the short duration of meteor trails, most messages require several trails for transmission. This causes low average data rates and results in long delay times (5:86).

#### *Transmission Protocols*

In most MBC systems transmission protocols play an important role. Because of the short meteor trail duration, protocols have to be very efficient to maximize throughput performance.

Two protocols will be used in this thesis. These protocols are referred to as Protocol 1 and Protocol 2. A fixed length packet is assumed for both protocols (20:632). The first protocol attempts to optimally use all available bursts. The terminal to receive data is assumed to be continually broadcasting a probe signal. The terminal sending the message data begins transmitting as soon as it hears the probing signal. As a result, the time delay is at most equal to the one-way propagation time. Once the channel closes, the probing signal disappears and data transmission stops; the search for a new channel opening now begins (20:632).

The second protocol examined uses the trail duration less efficiently. However, it is simpler to implement and it reduces the threat that a terminal might be detected

by decreasing the transmission requirements (20). In this protocol the message sending terminal probes for a channel. A channel is detected when the sending terminal receives an acknowledgement to its probe. This results in a delay almost equal to the two-way propagation time. Using this protocol, only one packet is transmitted per burst (21:147).

#### *MBC System Performance*

The performance parameters of greatest interest in military applications are the average throughput (in bits per second), average waiting time, probability of error, maximum range, and LPI/AJ capability (25:1594-1595). Performance of a meteor burst system is effected by several factors: background noise level, external interference, geographic location, season, and time of day. The effects of these factors can be counteracted by manipulating transmitted power, RF frequency, data rate, and antenna gain. Table 3.1 contains some typical meteor burst channel parameters.

Table 3.1. Typical Meteor Burst Channel Parameters

Carrier Frequency	40-110 MHz
Transmitter Power	200-2000 W
Bandwidth	100 KHz
Doppler Shift	5 Hz
Time Spread	1 $\mu$ s
Information Duty Cycle	2.5-5 percent
Average Message Delay	10-80 s
Worst Message Time	1-5 min

Increasing transmitted power enables meteor trail communication to take place for longer intervals of time because the trail can be used even as it begins to dissipate. This allows more information to be transferred during a single burst. Increased power also enables the use of trails formed by smaller meteoroids, which tend to occur more frequently than larger ones. The effect of increasing transmitted power is that it

increases both throughput and wait time. Increasing the operating frequency of a meteor burst system tends to decrease the effects present from nuclear detonations.

In comparison to other communication techniques, meteor burst is generally classified as long-range communications. As such, it must be compared to other forms of long-range communication such as telephone systems, microwave relay networks, HF radio, and satellite systems (16:27-28).

Telephone and microwave relay networks have the disadvantage of needing to have their equipment spaced fairly close to one another (this places limits on the type of terrain these systems can be based). Meteor burst systems only require hardware at each end of the communication path.

HF radio tends to have reliability problems at the higher latitudes. At high latitudes, message reliability can be as low as 30 percent. Schemes such as frequency diversity might help to increase the reliability to as much as 80 percent, but there are still severe blackout effects associated with auroral scatter. None of these factors tend to affect current meteor burst systems to any significant degree (16:27-28).

Satellite systems initially require a tremendous amount of capital investment. This is due to the cost of the ground stations and the satellite. For communication to take place, the satellite must be functional at all times. In the case of meteor burst systems, the cost of ground stations is minimal, the communication medium is self restoring and is free (16:28).

#### IV. MBC Theory of Propagation

This section of the thesis focuses on the structure of the meteor burst transmission equations and the development of equations for throughput, waiting time and the probability of successfully completing a message.

The performance of MBC systems is typically measured in terms of throughput, waiting time or the probability of successfully transmitting a message (21:146-147). While these factors are not the only parameters used, they are the most important to the system designer. Throughput is the measure of how many bytes of data are transmitted within one time unit. Waiting time is the time between the completion of one message and the start of another.

##### MBC Transmission Equations

The MBC transmission equations describe the variation of received power as a function of transmit power, transmit and receive antenna gains, path geometry, and operation frequency and time (28:122-123). Additional examples of MBC equations are listed in Appendix B.

Meteors with an electron line density of less than  $10^{14}$  electrons per meter of length are called underdense and those with greater density are called overdense. The equations for power received for the underdense and overdense case are respectively:

$$P_R(t) = \frac{P_T G_T G_R \lambda^3 q^2 r_e^2 \sin^2 \alpha \exp - \{8\pi^2 \cdot [(r_o^2 + 4Dt)/\lambda^2 \sec^2 \phi]\}}{16\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2 \beta \sin^2 \phi)} \quad (4.1)$$

$$P_R(t) = \frac{P_T G_R G_T \lambda^2 \sin^2 \alpha \left[ \frac{r_o^2 + 4Dt}{\sec^2 \phi} \cdot \ln \frac{r_e q \lambda^2 \sec^2 \phi}{\pi^2 (r_o^2 + 4Dt)} \right]^{1/2}}{32\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2 \beta \sin^2 \phi)} \quad (4.2)$$

where,

$P_R(t)$  = received carrier power

- $P_T$  = transmitted power
- $G_T$  = transmitting antenna gain
- $G_R$  = receiving antenna gain
- $\lambda$  = wavelength
- $q$  = electron line density of the trail
- $r_e$  = classical radius of an electron ( $2.85 \times 10^{-15} \text{ cm}$ )
- $\alpha$  = angle between the electric field vector  $E$  at the trail and  $R_R$
- $r_o$  = initial radius of the trail
- $D$  = diffusion coefficient
- $t$  = time
- $\phi$  = half the angle between  $R_T$  and  $R_R$   
(that is, the angle of incidence and reflection)
- $R_T$  = distance from the transmitter to the trail
- $R_R$  = distance from the receiver to the trail
- $\beta$  = angle between the principal axis of the trail and the  
plane formed by  $R_R$  and  $R_T$

The transmission equation for the overdense case will not be discussed. Most meteor burst communication is accomplished using underdense trails because they occur more often than overdense trails. A discussion of key parameters of the transmission equation follows.

The received carrier power,  $P_R(t)$ , is directly proportional to the transmitted power,  $P_T$ . This being the case, if all other factors are held constant, increasing the power output of the transmitter increases the SNR at the receiver and improves the performance of the MBC link. It should also be noted that there is a quadratic relationship between  $P_R(t)$  and the electron line density,  $q$ . Because of this relationship, a considerable variation in receiver SNR can be expressed between successive trails. For instance, all other factors held equal, the return from a trail of line den-

sity  $10^{12}e/m$  would be 40dB less than the return from a trail having line density of  $10^{14}e/m$ .

Another important parameter of the MBC transmission equation is the wavelength,  $\lambda$ . The wavelength parameter also implicitly describes how a change in frequency effects received power. Frequency and wavelength are inversely proportional as shown in the following equation:

$$\lambda = c/f \quad (4.3)$$

where  $c$  is the speed of light in a vacuum,  $3 \times 10^8 m/s$ . In equation 4.1  $\lambda^3$  appears in the numerator making it directly proportional to  $P_R(t)$  indicating that as the operating frequency increases, all other parameters held equal, the received power will decrease. The  $1/\lambda^2$  factor in the exponential term affects the lifetime of the trail. As the operating frequency increases, the characteristic lifetime of the trail decreases (28:125). This suggests that meteor burst communication systems are more efficient at lower frequencies.

Other terms that are of importance are the respective gain of the transmit and receive antennas,  $G_T$  and  $G_R$ . The angles of incidence and reflection between the trail and the stations are vital in determining the quality of transmission.

#### *MBC System Performance Measures*

The performance of a MBC system is usually measured in terms of either throughput or message waiting time. A probabilistic model of how a meteor burst channel behaves is useful in any analysis of a MBC system. Once this model is developed, expressions for waiting time and throughput can be derived.

*Probabilistic Model.* Oetting made significant strides in the development of math models for meteor burst communications (25:1598-1600). Several equations dealing with the performance of a meteor burst channel were derived. One of these

equations describes the probabilistic behavior of a meteor burst channel. Experimental studies have shown that the arrival of meteor trails suitable for communication can be modelled as a Poisson random process. In this model, the intervals between bursts are exponentially distributed and  $P_n(t)$ , the probability that exactly  $n$  bursts occur in time  $t$  is given by,

$$P_n(t) = \frac{(t/t_{IA})^n}{n!} \cdot \exp(-t/t_{IA}) \quad (4.4)$$

where  $t_{IA}$  is the average interval between bursts. This Poisson model for meteor burst arrivals has been confirmed by experimental tests (25:1598).

*Waiting Time.* The concept of the probabilistic model of the meteor burst channel can be extended to determine the probability of completing a message within a time  $t_D$  when more than one burst may be required. This probability can be expressed as

$$P_C(t_D) = \sum_{n=1}^{\infty} P_n(t_D) P_C(t_D | n) \quad (4.5)$$

where  $P_C(t_D | n)$  is the probability of completing the message in time  $t_D$ , given that exactly  $n$  bursts occur during this time, and  $P_n(t_D)$  is specified by equation 4.4 (25:1598).

Assuming that exactly  $n$  bursts occur during a time  $t_D$ , the total time available for communication is the sum of  $n$  independent random variables. Given that the individual burst times have an exponential distribution with average burst duration  $t_{BA}$ , a sum of  $n$  burst times will obey an Erlang distribution (25:1598). Using this fact, the probability that the total communication time will exceed a value  $x$  is

$$P_T(x) = \frac{1}{(n-1)!} \Gamma(n, x/t_{BA}) \quad (4.6)$$

where  $\Gamma(\cdot)$  is the incomplete gamma function. The total time to complete the message must equal or exceed  $t_M$  seconds where  $t_M$  is the message duration. These facts

can be used to modify equation 4.5 as

$$P_C(t_D) = \sum_{n=1}^{\infty} P_n(t_D) P_T(t_M). \quad (4.7)$$

Further manipulation of the gamma function in equation 4.6 yields

$$P_C(t_D) = \exp \left[ -\left( \frac{t_D}{t_{IA}} + \frac{t_M}{t_{BA}} \right) \right] \cdot \sum_{n=1}^{\infty} \frac{(t_D/t_{IA})^n}{n!} \cdot e_{n-1}(t_M/t_{BA}). \quad (4.8)$$

It was experimentally determined that equation 4.8 converges rapidly. Favorable results can be obtained by truncating the series after 20 terms (25:1599).

*Throughput.* The throughput of a meteor burst system is defined as the average number of correct data bits received per unit time. The throughput for the errorless transmission case is found by taking the expected value of the number of bits received in a time  $t_D$  and dividing the result by  $t_D$ .

The number of data bits transmitted in a time  $t_D$  is denoted by  $N_B$ . It is assumed that an ARQ scheme is used with  $I$  information bits and  $B - I$  parity bits comprising each  $B$ -bit block. The throughput for the errorless case is formed by manipulating the expectation of  $N_B$ , where  $N_B$  is expressed as

$$N_B = \sum_j j I N_j \quad (4.9)$$

where  $N_j$  is the number of bursts occurring in the time  $t_D$  that are able to support the transmission of exactly  $j$  ARQ blocks and  $j$  ranges over all positive integers. Taking the expected value of both sides of equation 4.9 gives,

$$E[N_B] = \sum_j j I E[N_j] \quad (4.10)$$

To find the expectation of  $N_j$ , the following identity must be used:

$$E[Y] = E\{E[y | x]\}. \quad (4.11)$$

Letting  $y = N_j$  and  $x = n$ , we get

$$E[N_j | n] = n \cdot Pr(N_j) \quad (4.12)$$

where  $Pr(N_j)$  is the probability that a burst can support exactly  $j$  ARQ blocks. The following expression is arrived at using equation 4.11 (25:1599)

$$E[N_j] = E[n] \cdot Pr(N_j). \quad (4.13)$$

For a Poisson process with an average interval between bursts of  $t_{IA}$ ,  $E[n]$  is given by

$$E[n] = t_D/t_{IA}. \quad (4.14)$$

$Pr(N_j)$  is dependent on the cumulative distribution of burst lengths. For the sectional logarithmic model,

$$Pr(t_B < x) = 0.235 \cdot \ln x - 0.784 \quad (4.15)$$

where  $t_B$  is the burst duration and  $Pr(\cdot)$  is the cumulative distribution function for burst durations. The expression for  $Pr(N_j)$  can be written as

$$Pr(N_j) = 0.235\{\ln[t_o + (j+1)t_A] - \ln[t_o + jt_A]\}. \quad (4.16)$$

This model assumes that the maximum duration of any burst is 2.5 seconds. Using this fact, equations( 4.13), ( 4.14) and ( 4.16) can be combined to solve for  $E[N_B]$

(25:1599). Dividing  $E[N_B]$  by  $t_D$  yields

$$T_o = 0.235(I/t_{IA}) \sum_{j=1}^J j \{ \ln[t_o + (j+1)t_A] - \ln[t_o + jt_A] \} \quad (4.17)$$

where  $T_o$  is the throughput and  $J$  is the largest value of  $j$  for which  $Pr(N_j)$ , the probability that a given burst can support exactly  $j$  ARQ blocks, is greater than zero, that is,

$$J \cong (2.5 - t_o)/t_A. \quad (4.18)$$

When the channel error rate is known, the results for the errorless case can easily be modified.

## *V. Development of a Parallel MBC Link Model*

The main objective of this thesis effort is to develop a parallel meteor burst communication link model. This chapter will describe the development of the necessary performance models and the methods used to test them. The models will be tested using computer simulation.

### *Queueing Model of an MBC Channel*

The random nature of meteor burst communications makes it suitable to be modeled as a queueing process. In particular the MBC process can be modeled using a M/G/1 queue with server vacations. An M/G/1 queue is a single server system with exponentially distributed interarrival times and a arbitrary service-time distribution. A server vacation represents a random loss of the server for a random amount of time (15:168).

In a meteor burst communication system messages are assumed to randomly arrive at the transmitter. The server in the MBC process is the meteor trail. Typical trail durations are on the order of 1 second, but their usefulness also depends on the radio path geometry, mass of the meteor, message length, trail height and transmission protocol used. The service time is assumed to have a general distribution (28, 21).

Random loss of service called server vacations occur when the received signal level (RSL) drops below the threshold of the receiver as the meteor trail dissipates (28). The time between service is derived from the meteor trail interarrival time and is a function of diurnal, seasonal, geographical location and engineering parameters. The interarrival time of meteor trails is assumed to have an exponential duration (28, 25). The service rate is determined by the transmitter bit rate and message protocol used (21:147).

The number of customers in a M/G/1 queue with server vacations represents the number of messages in a transmit buffer. This number is found to be the convolution of two probability generating functions (pgf) (9). One pgf is for the number of customers in a M/G/1 queue without server vacations and the other pgf depicts the number of arrivals during the residual of a vacation period (27, 8). The pgf for the number of customers in the M/G/1 system with server vacations is given by (8):

$$\pi(z) = \frac{K(z) \cdot (z - 1) \cdot (1 - \rho)}{z - C(z) \cdot K(z)} \cdot \frac{1 - C(z)}{\lambda - v \cdot (1 - z)} \quad (5.1)$$

where,

$C(z)$  = pgf for the number of arrivals during a vacation period

$\lambda$  = customer arrival rate

$K(z)$  = pgf for the number of arrivals during a service period

$v$  = average length of a vacation

$\rho$  = average arrival rate of customers

Laplace transforms have been derived for vacation durations, busy period density for service time and waiting time (8:567). The Laplace transform for the busy period density for service time is (14):

$$\alpha_B(s) = \alpha_T [s + \lambda - \lambda \cdot \alpha_B(s)] \quad (5.2)$$

where,

$\alpha_T$  = Laplace transform for service time

$\lambda$  = customer arrival rate

The Laplace transform for vacation durations was found to be (14:576):

$$v(s) = s + \lambda \cdot \alpha_T(s) - \lambda \quad (5.3)$$

where,

$\alpha_T(s)$  = Laplace transform for service time

$\lambda$  = customer arrival rate

The transform for waiting time was determined to be (14):

$$w(s) = s + \lambda - \lambda \cdot \alpha_B(s) \quad (5.4)$$

where,

$\alpha_B$  = Laplace transform for busy period density for service time

$\lambda$  = customer arrival rate

The equations mentioned above can be used to determine meteor trail duration, message wait time and meteor trail interarrival time. Note that the equations are based on the following assumptions:

1. Poisson arrivals,
2. first in first out (FIFO),
3. nonpreemptive service,
4. server vacations independent of customer arrivals,
5. infinite queueing capacity (14:580).

Assumptions 3 and 5 tend to be incompatible with MBC theory. Of the two, assumption 3 is most important because the server can preempt the transmission of a message through trail dissipation (9:48).

An effective service rate is determined by obtaining moments of the distribution for message transmission time (12). The equations used are as follows:

The distribution for message transmission time is:

$$B(t) = P(T \leq t) = 1 - \exp[-M^*(t - t_d)] \quad \text{for } t > t_d \quad (5.5)$$

where,

$B(t)$  = distribution for message transmission time

$M^*$  = the number off meteor trails long enough to completely  
transmit a message

$t_d$  = message duration

The Laplace transform of  $B(t)$  is:

$$\beta(s) = \frac{\exp[-s \cdot t_d] \cdot M^*}{s + M^*} \quad (5.6)$$

Moments of T are obtained from  $\beta(s)$ :

$$T^k = (-1)^k \cdot \frac{d^k}{ds^k} \cdot \beta(s) \quad (5.7)$$

The mean transmission time is:

$$T = \frac{1 + t_d \cdot M^*}{M^*} \quad (5.8)$$

The second moment of T is:

$$T^2 = \frac{[t_d]^2 \cdot (M^*)^2 + 2 \cdot [t_d] \cdot M^* + 2}{(M^*)^2} \quad (5.9)$$

Message delay was determined to be:

$$w = \frac{\mu \cdot T_2}{2 \cdot (1 - \rho)} \quad (5.10)$$

where,

$w$  = queueing delay

$\rho = \mu/M^*$

$\mu$  = message arrival rate

### *Parallel Link Model*

The major question to be answered in this thesis is how would the addition of a second parallel link effect the performance of a meteor burst channel? The term parallel link refers to having two simultaneous transmission paths between any two nodes of a network.

The parallel link concept used in this paper is based on transmitting a message between two nodes, using two different frequencies and the same meteor trail. Transmitting the message simultaneously creates a redundant path which should increase the probability of correctly receiving the message.

For the purpose of this study, it is assumed that the two paths formed by the parallel link concept are independent of one another. This is done to simplify the model. The parallel link model will be tested by simulation. The two simulation programs used are the meteor Burst Link (BLINK2) program and the Simulation Language for Alternative Modeling (SLAM II). The simulation will be carried out in two phases. In the first phase BLINK2 will be used. The BLINK program was developed by IBM and forms the baseline for BLINK2. BLINK2 is the result of several modifications made to BLINK. Both BLINK and BLINK2 are designed to be compatible with the IBM XT/AT. The BLINK2 program will serve as the front-end processor of the simulation model. The second part of the simulation model will be accomplished using SLAM II. In the SLAM II model each network node will be modeled as a pair of M/G/1 queues. This configuration adequately emulates a parallel link.

The meteor burst model used by BLINK2 incorporates equations derived by

Abel, Brown and Morin (9:51-52). Some of the equations used by BLINK2 are included in Appendix B. A more detailed description of the BLINK program can be found in (12). The input to the program consists of various engineering parameters which are then used to calculate meteor trail interarrival time, meteor trail duration and message duration (9, 12). The BLINK input data is uploaded from a data file. Some of the important input parameters are listed in table 5.1.

Table 5.1. Significant BLINK Input Parameters

BLINK2 INPUT Parameters			
1)	Range	10)	Message Site
2)	Frequency	11)	WTREL
3)	Month	12)	Line Losses
4)	Hour	13)	System Losses
5)	Transmitter Power	14)	Receiver Noise
6)	Transmitter Gain	15)	Man-Made Noise
7)	Receiver Gain	16)	Bit Energy to Noise
8)	Bit Rate	17)	Electron Density
9)	Probe Delay	18)	Terrain Index

The SLAM II portion of the model uses the values of meteor trail duration, message duration and meteor trail interarrival time computed by BLINK2 (9:54). Other inputs to the SLAM II module include the number of message bits, the transmission protocol to be used, probe response delay and message arrival rate. The SLAM II module is able to simulate networks using either Protocol 1 or Protocol 2. The input and output values of the SLAM II parallel link model are shown in table 5.2 and table 5.3. The models mentioned above were used to simulate the performance of three different networks. The networks are:

1. a 3-node relay network,
2. a 5-node ring network,
3. a 7-node hybrid network.

The results from the simulations will be compared to the results obtained by Healy (9:85-92).

Message routing tables were developed and implemented in SLAM II for each network topology. Each message routing table forms a  $N \times N$  matrix, where  $N$  is the number of nodes in the network.

The BLINK module is used to analyze each link in the network to provide meteor trail duration, message duration and meteor trail interarrival time. Other inputs needed to analyze each link are the probe response delay and transmission protocol. Each transmitter in the network requires the message size and arrival rate. The output from BLINK is then input into the SLAM II module.

Message transmission and probe delay tables are input into SLAM II to further define the network behavior. These tables are constructed in much the same way as the message routing tables. The values placed in the message transmission table represent message duration. The values in the probe delay table represent the probe response delay for each link in the network (9:57-58).

Each link in the network has a separate meteor trail arrival process. Each trail arrival process is initialized with the interarrival time calculated by BLINK. The probe response delay of each link is initialized with the link probe response delay when Protocol 1 is used (9:60). For the purpose of parallel link simulation, each node in the network is duplicated in SLAM II. When Protocol is used to send a message, the probe response delay in the arrival is null.

*Relay Network.* The ring network is made up of three nodes. In this network only nodes 1 and 3 create messages. Node 2 is a relay which receives messages from 1 and forwards them to node 3. Messages created at node 3 get transmitted directly to node 1.

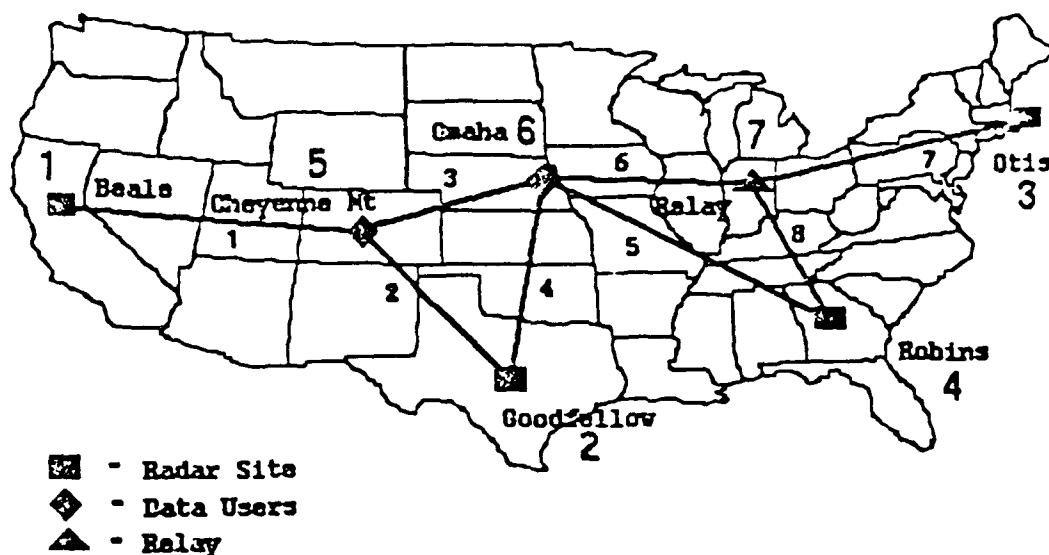
*Ring Network.* The ring network is made up of five nodes connected as two half-duplex rings. One set of lines comprises an outer ring and the other set makes an inner ring. In this network, each node creates messages. Each message has attributes which indicate the current transmitter and the final receiver. When messages are created, the starting node is the creation node and the final node is determined by the network (9:60-61). In this ring network, the creation and destination nodes are given in 5.4.

Protocol 1 is used for all nodes in this network. The current and final receiver nodes are used in conjunction with the message routing table to determine the transmission link. After transmitting a message, the link used to transmit the message is used to compute the new transmitter node. This process continues until the current transmitter node equals the final transmitter node.

*Hybrid Networks.* For the purpose of simulation, a hybrid network was developed. The hybrid network is composed of an arbitrary MBC network of PAVE PAWS sites. PAVE PAWS is a Phased Array Warning System used to provide early warning of submarine launched ballistic missiles (SLBM) attack. These sites send warning information, satellite tracking information and site status to several users. The data users for this test network will be the Cheyenne Mountain Complex and the SAC command post in Omaha. The network has seven nodes and eight links. The layout of the network is shown in the following figure 5.1. This network model uses a link range table instead of a message transmission table. The message duration per link is calculated from the range table.

Goodfellow AFB, Beale AFB and Robins AFB have PAVE PAWS sites. The NORAD Cheyenne Mountain Complex and Omaha AFB are data users. Only one relay is used in the network. Each PAVE PAWS site generates messages. These messages have a Poisson distribution (9:64). These messages represent missile warning information, satellite tracking information and status information sent to the

# PAVE PAWS Meteor Burst Network 1



## Network Topology

Site	Node	Latitude	Longitude
Beale	1	39.20	121.50
Goodfellow	2	31.40	100.40
Otis	3	41.70	70.50
Robins	4	32.60	83.60
Cheyenne	5	38.80	104.80
Omaha	6	41.20	96.00
Relay	7	41.00	87.00

Total Number of Links = 8

Figure 5.1. PAVE PAWS Network 1

two data users. Each data user receives the same message. Message destinations are shown in table 5.5. Messages created at the PAVE PAWS sites have 52C bits. Cheyenne Mountain creates messages once every ten minutes with destinations Beale, Goodfellow, Robins and Otis. These 132-bit messages contain status information. The messages created at Cheyenne Mountain have a deterministic distribution.

The results for the simulation of the network models mentioned above are contained in chapter VI. In this chapter, the parallel link results are compared to analytical results of Healy's single link model (9:85-92).

Table 5.2. SLAM II Parallel Link Model Input Values

SLAM II Input Values	
1)	Message Bits
2)	Probe Delay
3)	Message Arrival Rate
4)	Meteor Trail Duration
5)	Transmission Protocol
6)	Meteor Trail Interarrival Time
7)	Message Duration

Table 5.3. SLAM II Parallel Link Model Output Values

SLAM II Output Values	
1) Message Waiting Time	4) Throughput
2) Average Buffer Size	5) Transmission Time
3) Message Buffer Delay	6) Trails per Message

Table 5.4. Ring Network Nodes

Creation Node	Final Destination Node
1	3
2	5
3	1
4	1
5	2

Table 5.5. PAVE PAWS Network Nodes

Creation Node	Final Destination Node
Beale	Omaha
Goodfellow	Cheyenne Mountain
Goodfellow	Omaha
Otis	Cheyenne Mountain
Robins	Cheyenne Mountain

## *VI. Results*

This chapter contains the modeling results for the networks mentioned in the previous chapter. It also contains comparisons of analytical MBC data to the results obtained by using BLINK and BLINK2.

The network models were validated by comparing the simulated results with analytical results computed by BLINK2. Both Protocol 1 and Protocol 2 were used in this validation process.

### *Analytical Results for Meteor Arrival Rate*

In the following figures, the predicted results for BLINK and BLINK2 are compared to analytical data. The analytical data was obtained from tests on the RADC high-latitude MBC link (12:22-23). The received signal level (RSL) is given in dBm, and it represents the receiver detection threshold. The number of detectable trails decreases as the RSL increases because weak signal returns are rejected by the receiver. This fact is illustrated in table 6.1 and table 6.2.

### *Validation*

The simulation results for the throughput and delay characteristics of a MBC channel were validated by comparing them to results obtained using BLINK and BLINK2. Both protocols were used to validate the throughput values. Only Protocol 2 was used to verify the simulation delay results.

Protocol 1 was validated first. The methods used to validate Protocol 1 are as follows. The first method treats messages as distinct groups of bits with a certain message duration. The second method disregards message boundaries and considers buffered messages as a single collection of bits. The second method uses trail duration in its throughput calculation rather than message duration. A comparison of the two

Table 6.1. Meteor Arrival Rate at a Frequency of 45 MHz

1100 December at 45 MHz			
Meteors per Minute			
RSL (dBm)	Analytical	BLINK	BLINK2
-120	4.80	4.40	3.80
-119	4.60	3.80	3.10
-118	4.10	3.10	2.80
-117	3.80	2.90	2.50
-116	3.40	2.60	2.30
-115	3.10	2.40	2.10
-114	2.90	2.20	2.00
-113	2.50	2.10	1.80
-112	1.90	1.70	1.50
-111	1.50	1.50	1.30
-110	1.30	1.30	1.20
-109	1.20	1.20	1.10
-108	0.90	1.10	0.90
-107	0.80	0.90	0.85
-106	0.60	0.80	0.70
-105	0.50	0.70	0.60
-104	0.40	0.60	0.50
-103	0.35	0.54	0.45
-102	0.30	0.50	0.40
-101	0.25	0.45	0.38
-100	0.10	0.40	0.36
-99		0.35	0.35
-98		0.30	0.30
-97		0.25	0.25
-96		0.20	0.20
-95		0.15	0.15

Table 6.2. Meteor Arrival Rate at a Frequency of 104 MHz

1100 December at 104 MHz			
Meteors per Minute			
RSL (dBm)	Analytical	BLINK	BLINK2
-112	0.45	0.50	0.39
-111	0.38	0.46	0.35
-110	0.29	0.41	0.31
-109	0.22	0.36	0.28
-108	0.18	0.32	0.25
-107	0.10	0.25	0.19
-106	0.09	0.23	0.18
-105	0.85	0.21	0.17
-104	0.08	0.20	0.16
-103	0.06	0.18	0.14
-102	0.03	0.16	0.13
-101	0.02	0.14	0.11
-100	0.01	0.12	0.10

methods indicates that method 2 is more accurate than method 1. The input to the SLAM II parallel link model was as follows:

Meteor Trail Interarrival Rate = 15.266 sec,  
 Transmitter Bit Rate = 8000 bps,  
 Message Bits = 1024,  
 Message Duration = 0.138 sec,  
 Probe Response Delay = 0.030 sec

Protocol 2 was validated in the same fashion as Protocol 1.

Throughput values for Protocol 1 and 2 are given in the table below:

Table 6.3. Throughput for Protocols 1 and 2

MSGs/MIN	PROTOCOL 1 THROUGHPUT (bps)	PROTOCOL 2 THROUGHPUT (bps)
0.5	9	9
1.0	18	18
2.0	36	36
3.0	52	52
4.0	67	67
5.0	81	82
6.0	101	100
7.0	124	119
8.0	140	122
9.0	160	131
10.0	177	133
11.0	190	
12.0	199	
13.0	207	
Analytical Tput for P1 = 175		

### *Network Model Results*

Only the results for the PAVE PAWS network will be discussed in this section. This network model was chosen so that the utility of using MBC as a backup means of communication for the Attack Warning and Attack Assessment (AW/AA) segment of the ITW&A network. The input parameters for BLINK2 are listed in table 6.4. The input parameters for the SLAM II portion of the model are obtained from BLINK2. The input parameters are given in table 6.5.

Once the process is completed, the results can be evaluated. The results from the input parameters shown in table 6.5 are given in table 6.6. The data presented in table 6.6 shows that the most efficient link in the entire network is the link between Goodfellow and Omaha. This performance is attributed to the distance between the sites and the transmission frequencies used on the parallel link. The worst link in the network is the link from Robins to Omaha. The degradation in performance is primarily due to the distance between the two sites. A table showing the difference between the parallel link model results and the single link model of Healy is shown below in table 6.7. It is shown that the parallel link model out performs the single link model. This is attributed to the redundancy obtained by having parallel paths to each site. The modest increase in performance obtained using the parallel link model would not warrant the full scale implementation of a parallel link network. A possible implementation would be to only use this model to enhance the slower links of a network causing the network to achieve better overall performance.

Table 6.4. BLINK2 Input Parameters

		1) Range (km)	2) Frequency (MHz)
LINK	1	1440.9	30
LINK	2	914.1	40
LINK	3	794.7	50
LINK	4	1157.7	30
LINK	5	1455.9	40
LINK	6	753.6	50
LINK	7	1376.5	30
LINK	8	981.0	40
		8) Transmitter Bit Rate (bps)	Message Bits
NODE	1	8000	520
NODE	2	8000	520
NODE	3	8000	520
NODE	4	8000	520
NODE	5	8000	132
3)	Month		May
4)	Hour		1100
5)	Transmitter Power (W)		1000
6)	Transmitter Gain (dBi)		10
7)	Receiver Gain (dBi)		10
9)	Probe Response Delay (sec)		0.03
11)	Line Losses (dB)		1.00
12)	System Losses (dB)		1.00
13)	Receiver Noise (dB)		4.00
14)	Man Made Noise Factor		1
15)	Bit Energy to Noise (dB)		9.0
16)	Terrain Factor		0
17)	Electron Line Density (el/m)		$5 \times 10^{13}$

Table 6.5. SLAM II Input Parameters

		Beale	Goodfellow	Otis	Robins	Cheyenne
1)	Msg Arrival Rate (msgs/min)	3	3	3	3	3
5)	Probe Delay (sec)	0.03	0.03	0.03	0.03	0.03
6)	Message Bits	520	520	520	520	132
		2) IA		3) BDUR	4) MDUR	7) Protocol
LINK	1	15.284		0.455	0.070/0.022	2
LINK	2	12.062		0.639	0.071/0.023	2
LINK	3	14.757		0.486	0.070/0.022	2
LINK	4	9.994		0.793	0.073/0.024	2
LINK	5	18.478		0.167	0.075/0.026	2
LINK	6	15.242		0.487	0.070/0.022	2
LINK	7	13.769		0.544	0.074/0.026	2
LINK	8	11.577		0.613	0.072/0.023	2
		IA - Trail Interarrival Time				
		BDUR - Burst Duration				
		MDUR - Message Duration				
		520 bits/132 bits				

Table 6.6. SLAM II PAVE PAWS Parallel Link Network Output

Transmission Time (sec)	Time
Link 1	10.69
Link 2	7.97
Link 3	9.17
Link 4	6.13
Link 5	16.26
Link 6	9.20
Link 7	9.50
Message Waiting Time (sec)	Time
Beale to Omaha	42.77
Goodfellow to Omaha	39.22
Goodfellow to Cheyenne Mountain	15.77
Otis to Cheyenne Mountain	77.85
Robins to Cheyenne Mountain	92.50
Throughput	bps
Beale to Omaha	27.9
Goodfellow to Omaha	36.2
Goodfellow to Cheyenne Mountain	38.0
Otis to Cheyenne Mountain	28.3
Robins to Cheyenne Mountain	34.5

Table 6.7. Comparison of Parallel and Single Link Network Output

	Parallel-Link	Single-Link	
Transmission Time (sec)	Time	Time	
Link 1	10.69	10.68	
Link 2	7.97	7.96	
Link 3	9.17	9.17	
Link 4	6.13	6.12	
Link 5	16.26	16.25	
Link 6	9.20	9.18	
Link 7	9.50	9.50	
Message Waiting Time (sec)	Time	Time	% Change
Beale to Omaha	42.77	49.88	14.25
Goodfellow to Omaha	39.22	44.13	11.13
Goodfellow to Cheyenne Mountain	15.77	22.45	29.76
Otis to Cheyenne Mountain	77.85	84.40	7.76
Robins to Cheyenne Mountain	92.50	107.50	13.95
Throughput	bps	bps	% Change
Beale to Omaha	27.9	24.1	15.77
Goodfellow to Omaha	36.2	28.6	26.75
Goodfellow to Cheyenne Mountain	38.0	32.0	18.57
Otis to Cheyenne Mountain	28.3	24.6	15.04
Robins to Cheyenne Mountain	34.5	28.2	22.30

## *VII. Recommendations for Future Research*

The understanding of meteor burst communication systems is evolving continuously. As this trend continues, there will be many new applications for this technology. This final chapter of the thesis deals with probable applications and areas which need more investigation.

The following are areas needing further review:

1. Integrate MBC systems with the Integrated Digital Services Network (ISDN). Develop a meteor burst network that has the capability to interface with this powerful network. The MBC network need only exploit one facet of ISDN to be a viable system.
2. A study of MBC systems ability to operate in the face of a nuclear environment is needed. More data is needed in this area to further quantify meteor burst communication's effectiveness verses other forms of communications.
3. Further develop the idea of a highly survivable MBC network. Simulation models should be developed to emulate a highly interconnected MBC network.
4. Study the utility of using a feedback adaptive variable-bit-rate system as a means of maximizing throughput and minimizing the waiting time of a MBC channel.
5. Develop a constellation of interoperable MBC networks. This will involve determining the types of interfacing equipment needed to perform translations between the various networks. A great deal of work will also have to go into integrating the Open Systems Interconnect (OSI) seven layer network model into existing and future MBC networks.
6. Develop a method whereby MBC networks can interface with other military networks such the GPS system. The study would determine the necessary

requirements needed to enable mobile MBC terminals to communicate with such diverse systems.

## Appendix A. *Glossary of Terms*

**Adaptive Routing** Message routing algorithm in which a transmitter sends messages to different network nodes determined by current message traffic

**ARQ** Automatic Repeat Request

**BLINK** Advanced reference type meteor burst communications prediction model developed by IBM (Burst Link)

**C<sup>3</sup>I** Command, Control, Communications and Intelligence

**Flood Routing** Message routing algorithm in which a transmitter sends messages to all network nodes

**HF** High Frequency

**ITW&A** Integrated Tactical Warning and Assessment

**km** Kilometer

**LPI/AJ** Low Probability of Intercept (LPI) and Antijam capability (AJ)

**MBC** Meteor Burst Communication

**MHz** Megahertz

**Overdense Meteor Trails** Meteor trails with an electron line density greater than  $2 \times 10^{14} \text{electrons/meter}$

**PCA** Polar Cap Absorption

**PAVE PAWS** Phased Array Warning System

**RADC** Rome Air Development Center

**SLAM II** Simulation Language for Alternative Modeling developed by A. Pritsker

**Static Routing** Message routing algorithm in which each transmitter delivers messages to a specific network node through the use of a routing table

**Underdense Meteor Trails** Meteor trails with an electron line density less than  
 $2 \times 10^{14} \text{electrons/meter}$

## Appendix B. *Significant MBC Equations*

This appendix contains formulas that were used in the development of the parallel link meteor burst model. Most of the equations listed below were used in the BLINK program.

$$h = -17 \cdot \log(Fq) + 124 \quad (\text{B.1})$$

$$D = 10^{(0.067 \cdot h - 5.60)} \quad (\text{B.2})$$

$$r_o = 10^{(0.035 \cdot h - 3.45)} \quad (\text{B.3})$$

where,

$h$  = Meteor Height (Km)

$D$  = Ambipolar Diffusion Coefficient ( $m^2/sec$ )

$r_o$  = Meteor Trail Radius (m) (2)

---

The next equation is used to caculate the power factor (24:69).

$$N_o = 10 \cdot \log \left[ k \cdot T_o \cdot \left[ \left[ \frac{104}{L_R} \right] \cdot \left[ \frac{20}{Fq} \right]^{2.3} \cdot [N_M]^2 + F \right] \right] \quad (\text{B.4})$$

$$P_{TH} = N_o + 10 \cdot \log(\text{Brate}) + \text{ETON} \quad (\text{B.5})$$

where,

ETON = Energy to Noise Ratio

$N_o$  = Noise Power Spectral Density (dbW/Hz)

$P_{TH}$  = Receiver Detection Threshold (dBW)

Brate = Bit Rate

$k$  = Boltzman's Constant (J/K)

$L_R$  = Line Losses (W)

$F_q$  = Frequency

BLINK uses the assumption that the distance between the receiver and the meteor trail is equal to the distance from the transmitter to the trail =  $R(1.927)$ .

$$R = \sqrt{\frac{Ra^2}{4} + \left[h + \frac{Ra^2}{8 \cdot R_e}\right]^2} \quad (B.6)$$

$$\cos(\beta) = \frac{2}{\pi} \cdot \sin(\phi) = \left[1 + \left[\frac{2 \cdot h}{Ra} + \frac{Ra}{4 \cdot R_e}\right]^2\right]^{-0.5} \quad (B.7)$$

$$PFRA = 10 \cdot \log \left[ \frac{R^3 \cdot [1 - \cos(\beta)^2 \cdot \sin(\phi)^2]}{R_{TL}^3 \cdot [1 - \cos(\beta)^2 \cdot \sin(\phi_T)^2]} \right] \quad (B.8)$$

Convert the power and the system losses to dB:

$$P_T = 10 \cdot \log [P_T] \quad L_S = 10 \cdot \log [L_S] \quad (B.9)$$

$$PF = P_T + G_T + G_R - P_{TH} - L_S - PFRA \quad (B.10)$$

where,

PFRA = power factor range adjustment (dB)

Ra = range

PF = power factor (dB)

$\beta$  = angle formed between the trail and the range of the transmitter  
and the range of the receiver

$L_S$  = system and line losses (dB)

$G_T$  = transmitter antenna gain

$G_R$  = receiver antenna gain (12:3-4,3-5)

---

The equations below are used to calculate the unadjusted meteor bursts per minute

(UMBPM): The frequencies are in hertz. The UMBPM is represent in the equations as (M).

$$MH = 10 \left[ \left[ \frac{PF - PF_T}{20} \right] + 1.5 \cdot \log \left[ \frac{Fq_T}{Fq} \right] \right] \quad (B.11)$$

$$MH = MH \cdot MH_T \cdot AF \cdot MF_{month} \cdot HF_{hour} \quad (B.12)$$

$$M = \frac{MH}{60} \quad (B.13)$$

where,

$MF_{month}$  = month scale factor

MH = total number of meteor bursts per hour detected by a transmitter

$PF_T$  = power factor on the test link

$Fq_T$  = frequency on the test link

AF = antenna factor

$HF_{hour}$  = hour scale factor (12)

Calculate the characteristic trail lifetime (24:28).

$$\sec(\phi) = \sqrt{1 + \left[ \frac{Ra^2}{\left[ 2 \cdot h + \left[ \frac{Ra^2}{4 \cdot R_e} \right] \right]^2} \right]} \quad (B.14)$$

$$t_c = \frac{\lambda^2 \cdot \sec(\phi)^2}{16 \cdot \pi^2 \cdot D} \quad (B.15)$$

where,

$R_T$  = the range between the trail and the transmitter

$t_c$  = characteristic meteor trail lifetime (sec)

$\lambda$  = wavelength of the transmitted signal

$\phi$  = half the angle between  $R_T$  and  $R_R$

$R_T$  = the range between the trail and the transmitter

$R_R$  = the range between the trail and the receiver

---

Calculate the underdense trail duration (24:16-24). Initialize  $\alpha$  and  $\beta$  to  $\pi/2$ . Received power level:

$$P_R(t) = \frac{P_T G_T G_R \lambda^3 q^2 r_e^2 \sin^2 \alpha \exp -8\pi^2 \cdot [(r_o^2 + 4Dt)/\lambda^2 \sec^2 \phi]}{16\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2 \beta \sin^2 \phi)} \quad (\text{B.16})$$

$$t_u = [P_R(0) - P_{TH}] \cdot \left[ \frac{t_c}{8.7} \right] (\text{sec}) \quad (\text{B.17})$$

The power values expressed in equation B.17 are in dBW. where,

$P_R(t)$  = received carrier power

$t_u$  = usable trail duration (sec)

---

Message Waiting Time is equal to:

$$t_{IA} = 60/M \quad (\text{B.18})$$

$$\text{wait1} = -t_{IA} \cdot \ln(1 - \text{wtrel}) \quad (\text{B.19})$$

$$\text{wait2} = \frac{-60}{M^*} \cdot \ln(1 - \text{wtrel}) \quad (\text{B.20})$$

where,

wait1 = message waiting time for protocol 1

$t_{IA}$  = meteor trail interarrival time (sec)

wait2 = message waiting time for protocol 2

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## *Abstract*

Meteor burst communication (MBC) constitutes an unusual propagation medium with many unique and interesting properties. These properties make MBC well suited for military applications. MBC offers many advantages over other forms of existing long range communication systems. Some of the advantages include low probability of intercept (LPI), antijam (AJ), flexibility and survivability. The LPI/AJ characteristics of MBC are the most important to military applications. MBC also suffers from two major drawbacks: long message delay times and low throughput. As a result, MBC systems exhibit low average data rates and long delay times. In order for MBC to gain widespread use, methods to optimizing system performance must be developed. The result of this study effort is the development of a parallel MBC link model that is used to analyze MBC network performance.

To address this issue, a computer model was developed to emulate a PAVE PAWS parallel link MBC network. This unique model was developed using the queueing model for a MBC channel. The queue used is a M/G/1 queue with server vacations. The model was implemented using two simulation programs which are supported on the IBM PC. The results of the simulation are validated by comparison to analytical data.

The results gathered in this study effort indicate that some performance gains are attainable if a MBC network is modeled using a parallel link model. It is shown that moderate increases in throughput and a reduction in message waiting time is possible.